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AFTA-WFIRST Coronagraph Instrument Status Report -- SDT

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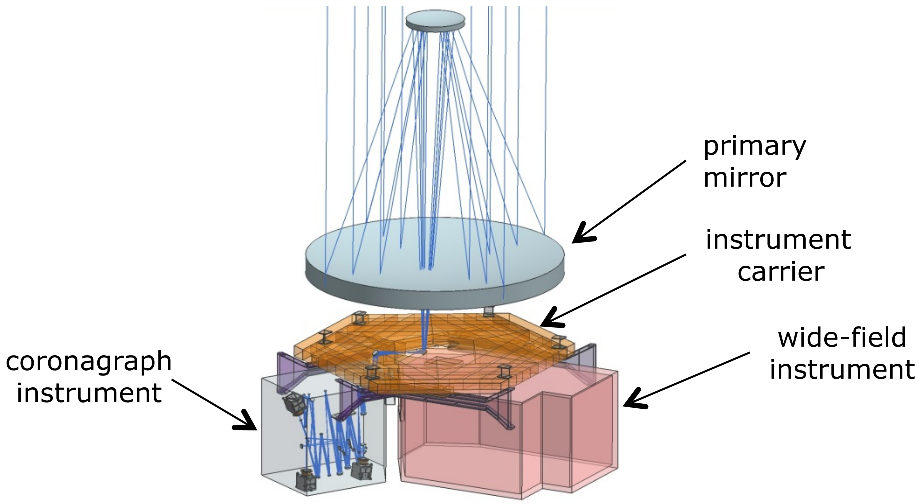
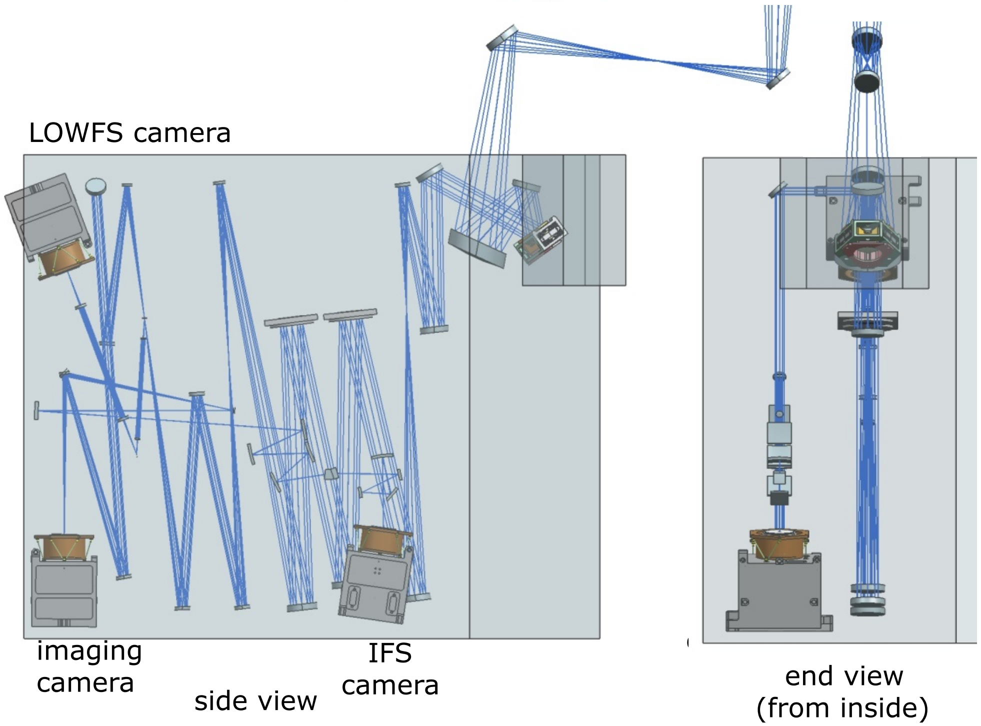
Outline

- Coronagraph design status
- Technology development progress
  - Coronagraph masks
  - LOWFS
  - Low noise detector
- Next steps
- Summary

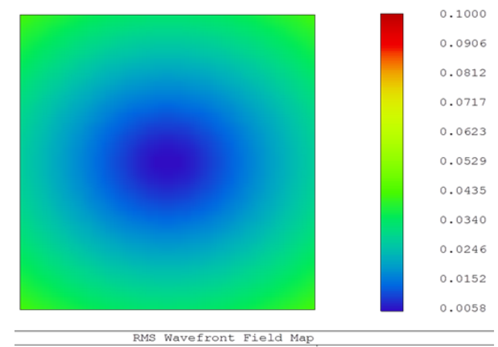
Coronagraph Instrument





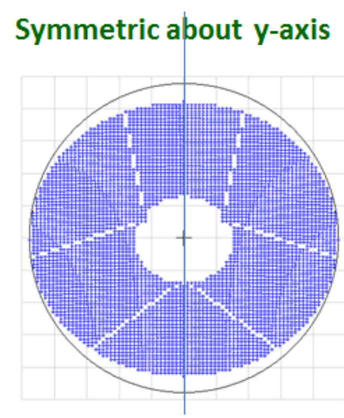
Major changes from last report:

- Off-axis angle from 0.6 to 0.4 deg (2X WFE improvement)
- Fold mirrors from 1 to 2 (eliminated asymmetry)



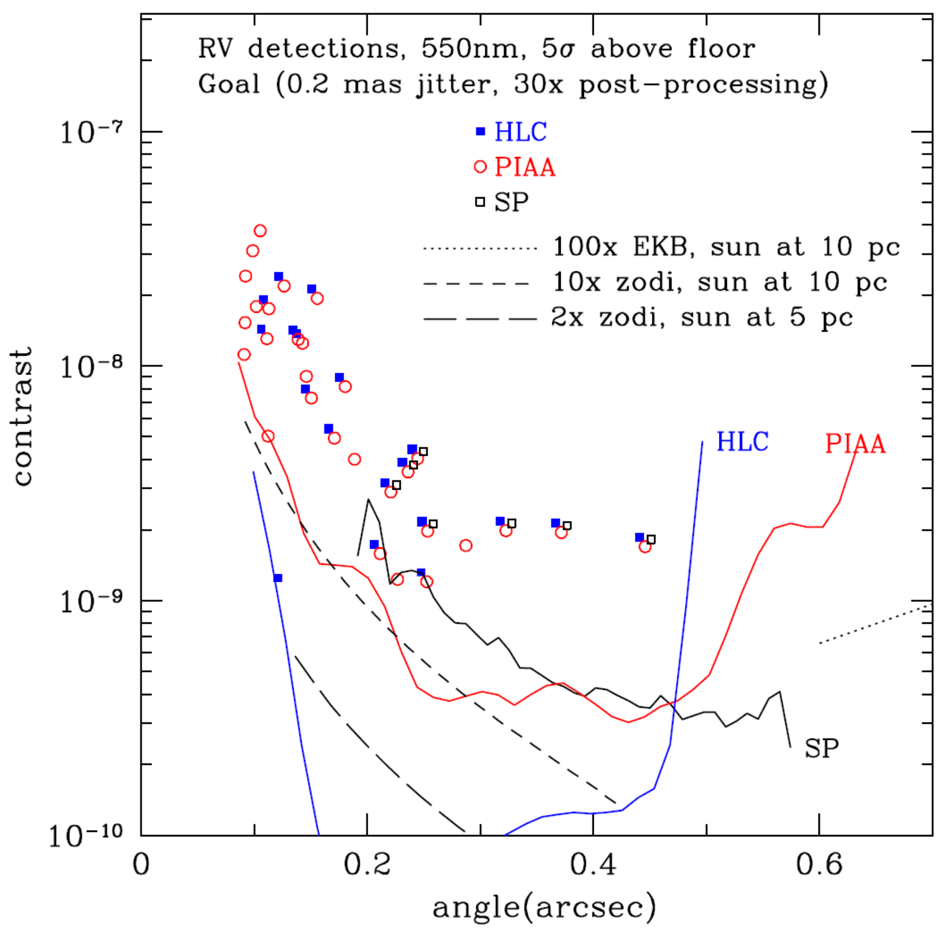
RMS max = 0.043nm

Symmetric about y-axis



Predicted Radial Velocity Planet Detection and Spectroscopy

Best Estimates based on Low Jitter and Post-Processing



Contrast (planet/star brightness ratio) of detectable known RV planets, vs angular separation from star

<u>Solid lines</u>: 5-σ detection limits

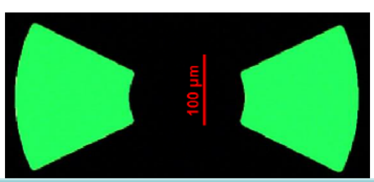
<u>Points</u>: detectable RV planets for each coronagraph

<u>Dashed lines</u>: zodiacal disk & Edgeworth-Kuiper disk brightness around sun, at 5 & 10 pc, scaled to denser values than in solar system

HLC: Hybrid Lyot Coronagraph
SP: Shaped Pupil Coronagraph
PIAA: Phase Induced Amplitude Apodization Coronagraph

SPC Status: Reflective Mask

Stitched microscope images



Bow-tie focal plan mask image

- Mask design received from Princeton and translated into machine language
- Two iteration of reflective shaped pupil masks were fabricated at JPL and Caltech
  - Noticeably reduced defects from 1st to 2nd iteration due to process improvements
- Fabricated bow-tie focal plane mask
- **Shaped Pupil mask for coronagraph testbed is on schedule for April 3rd delivery**.

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HLC Mask Fabrication Status

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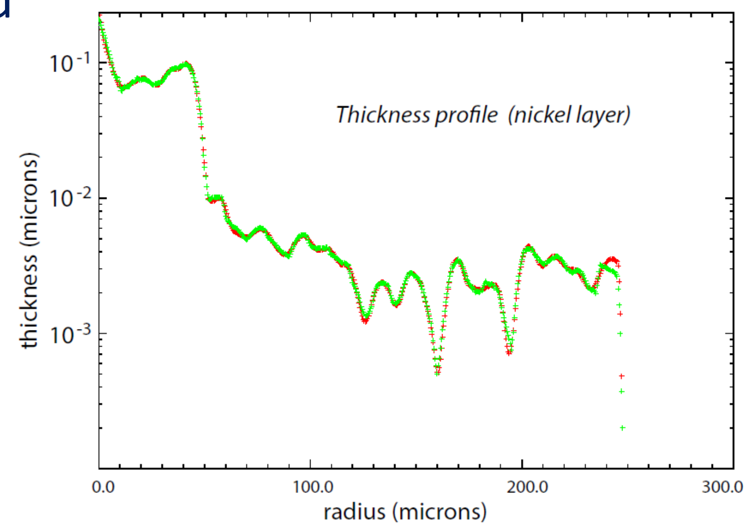
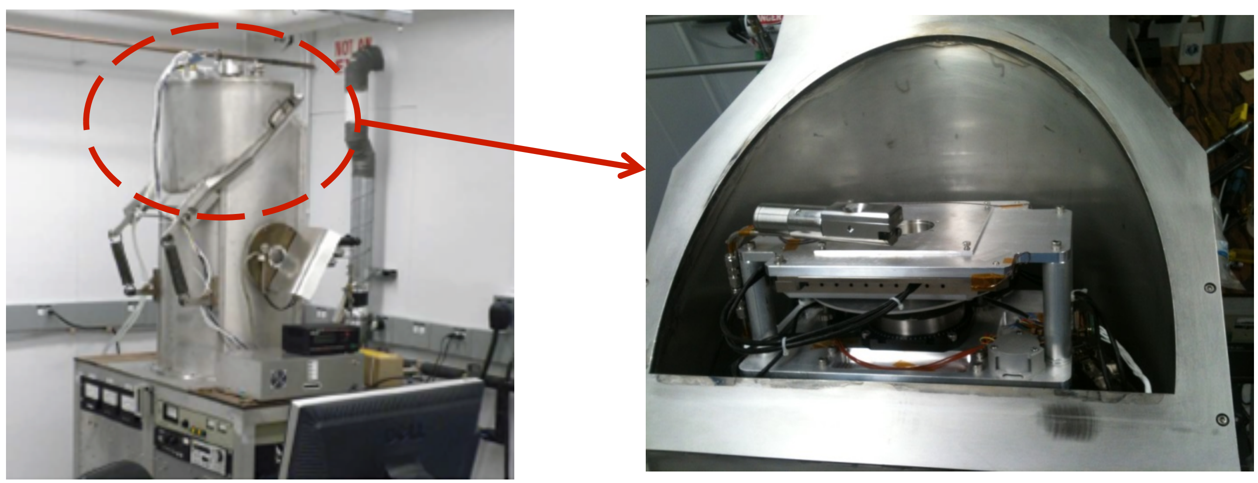
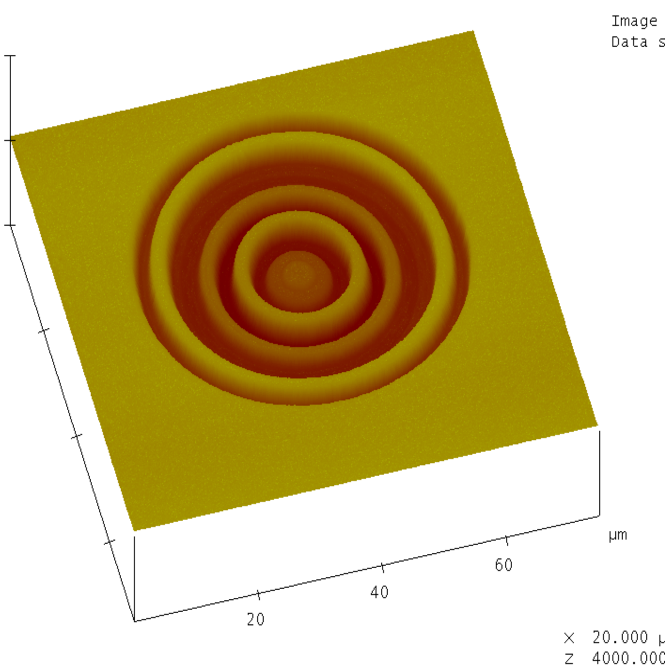
- Deposition fixture fabricated and installed into the chamber
- Fused Si substrates, micro-stencil plate and alignment reticle fabricated
- Simulations predict good agreement between the desired and actual thickness profiles for the selected set of micro-stencils
- Targeting first mask delivery for May 2014

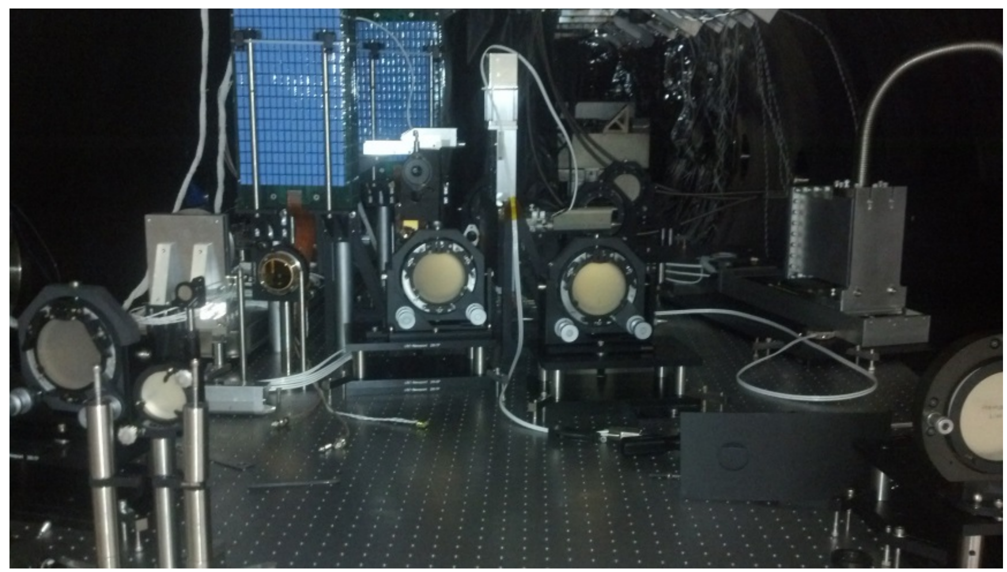




PIAA-CMC Status

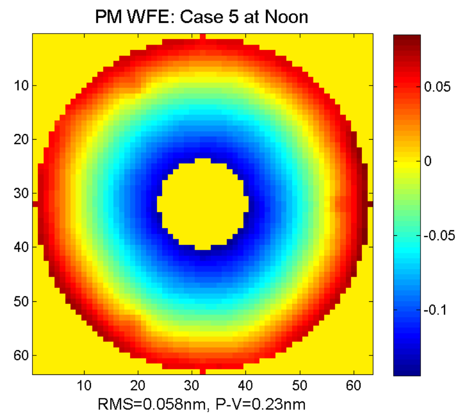
- First set of PIAA-CMC narrowband phase-only focal plane masks has been made using e-beam lithography at JPL's MDL
- Mask characterization results look promising
- Mask installed in the aligned PIAA testbed (with stopped-down old PIAA mirrors)
- Testbed is under vacuum in HCIT2 tank at JPL
- Accelerated PIAA-CMC plan – a collaboration of UofA, JPL, and ARC – has been reviewed by the team

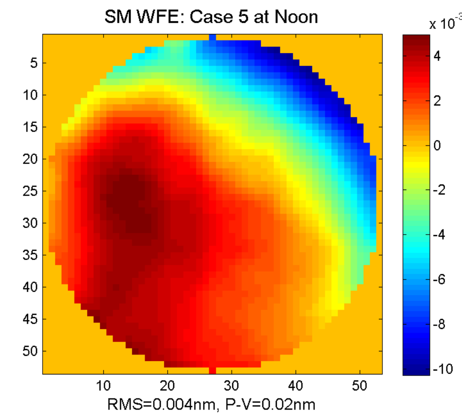


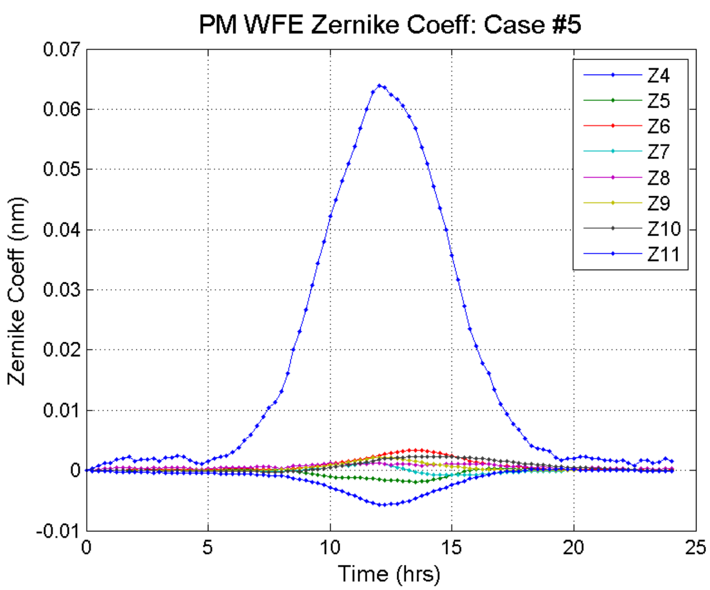


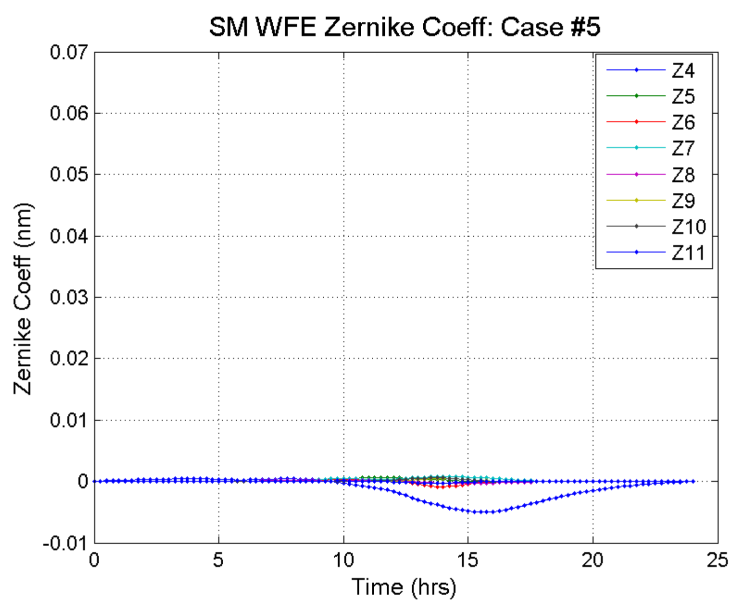
LOWFS: Impact of Telescope Drift on Coronagraph Performance

- AFTA PM & SM thermal surface figure drift induced WFE is used to evaluate their impact on coronagraph contrast (**Cases # 5-6 are typical**)
- For each thermal drift case the maximum WFE over the 24 hour period is used



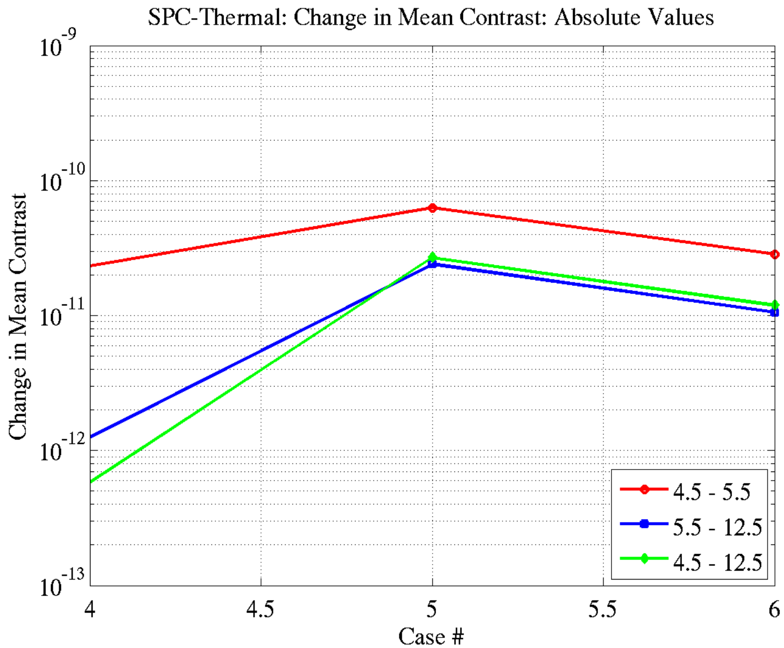


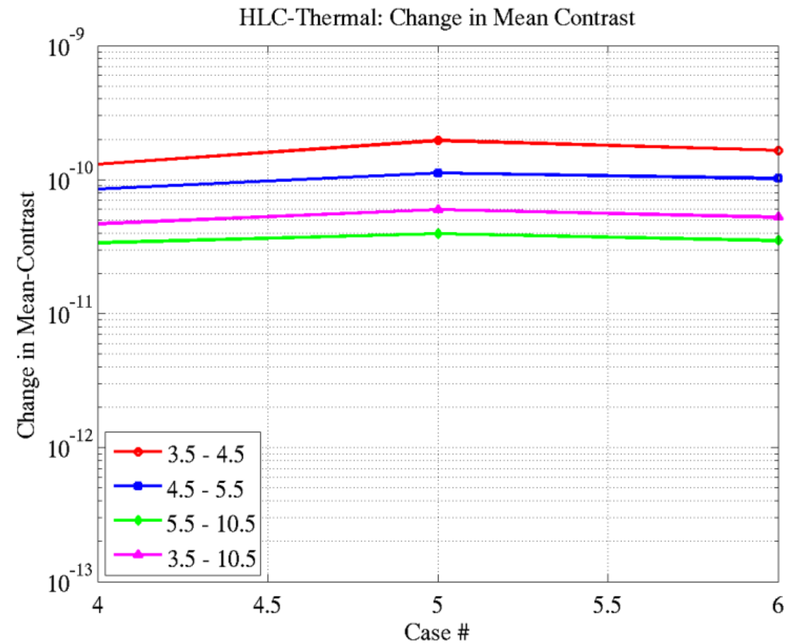




LOWFS: Impact of Telescope Drift on Coronagraph Performance

- The change of contrast from WFE evaluated using J. Krist's PROPER model (low jitter HLC design) end-to-end contrast change analysis is shown below
- Mean contrast **changes** (Δ contrast) are calculated over dark hole regions of 3.5 – 4.5, 4.5 – 5.5, 5.5 – 10.5 and 3.5 – 10.5 λ/D





- **Impact to contrast from thermal low-order wavefront changes is < 10^{-10} (same for RB effects)**
- **Hence LOWFS/C performance beyond tip/tilt is not as critical as previously assumed**
- **Tip/tilt sensing and control still necessary for HLC and PIAA-CMC**

Coronagraph Detectors - Oveview

- The low photon rates from the planets calls for low-noise focal plane arrays
- We have put together a preliminary model of the imager and IFS SNR using the PROPER model results for coronagraph performance
- The preliminary results suggest that, for the coronagrah:
  - using conventional CCD's there can be a meaningful science yield,
  - but using EMCCD's there can be savings of ~90% in intergration time
- The story to follow…

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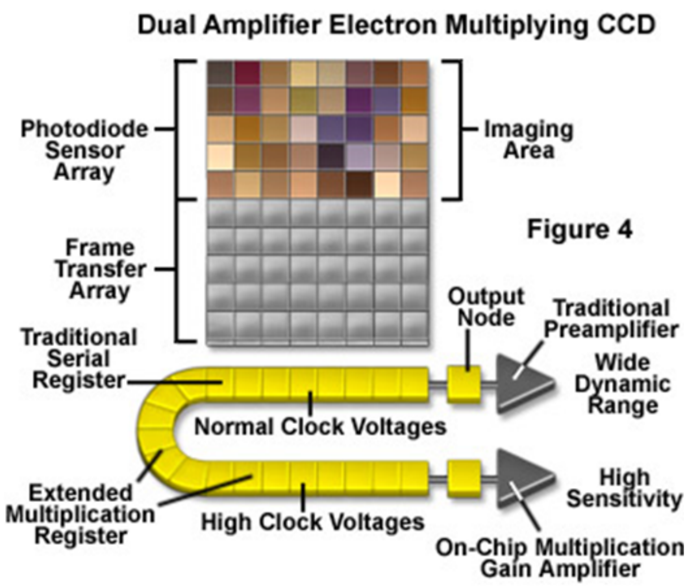
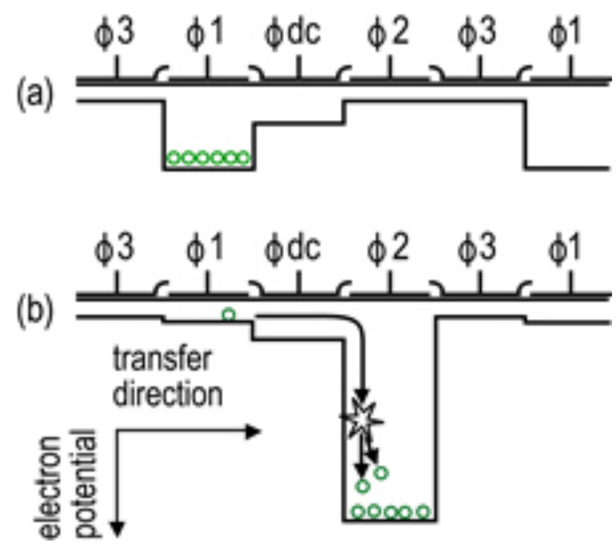
CCD's with Electron Multiplication Option (EMCCD)

- In traditional CCD's the pixels are clocked out in parallel into a serial register where they are then read out.
- In an EMCCD they are routed instead to an extended multiplication register with a high-voltage phase (10's of V) where they undergo multiplication
- At each gain stage there is a small (typically < 2%) chance of getting an extra electon (i.e. multiplication)
- Since there are hundreds of multiplication elements there can be a large gain:

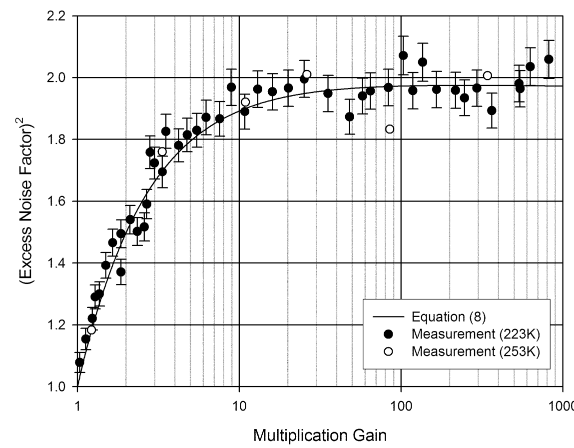
$$M = (1+p)^N \qquad \text{e.g.} \quad (1+1.5\%)^{600} \approx 7500$$





Consequences of Electron Multiplication

- The main benefit of electron multiplication is a boost to the signal while the read noise per read is still the same as for ordinary CCD
  - This effectively translates to a <u>proportionately lower read noise</u>



- Some Drawbacks:
  - The full-well (hence dynamic range) is proportionately reduced
    - but not a big issue in low light
  - The electron multiplication is a stochastic process, so that the gain is not the same every time
    - this introduces an **'excess noise factor' (ENF)** $\sim\sqrt{2}$
      - this effectively halves the QE
      - but this can be mitigated in photon counting mode
  - The high voltages and high frequencies implied in acquisitions using an EMCCD are the sources of **clock-induced charge (CIC)** $\sim 10^{-3}$ e-/pix/frame**.** These electrons are generated during the transition of the electrical signals from one well to another used to read the EMCCD.
    - these can be reduced by optimizing the clocking parameters

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An Additional Possibility: Photon Counting

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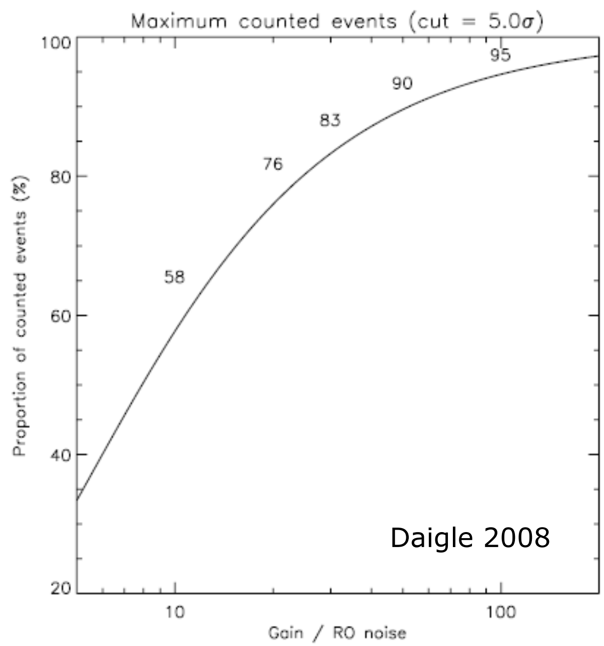
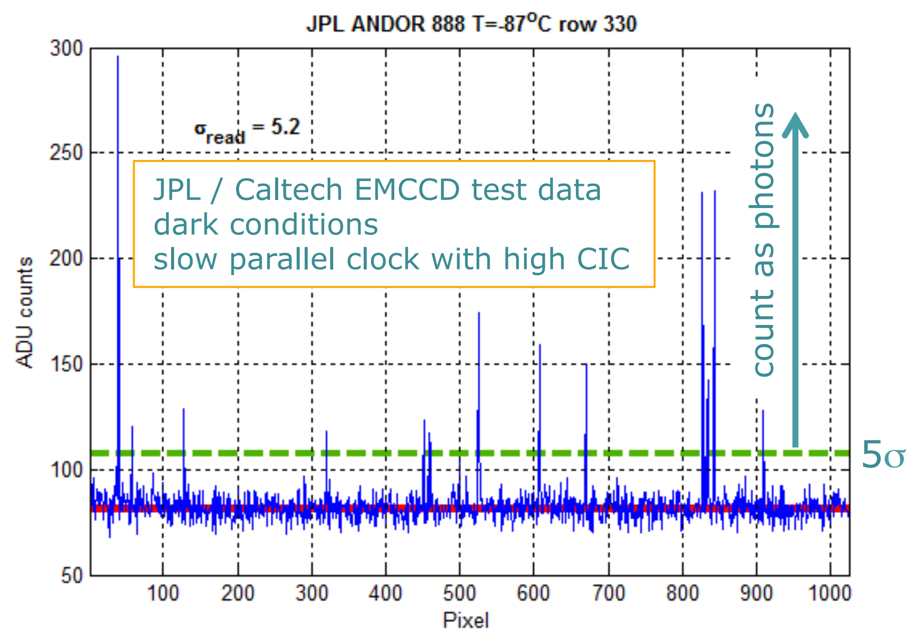
- If there are almost never > 1 photons likely to hit a pixel in one frame time, can go into photon counting mode
- Here we set a threshold high enough to avoid false positives but low enough not to lose efficiency (see below)
- **The advantage of photon counting is that the excess noise factor is eliminated, equivalent to restoring the QE**
  - **This in turn amounts to ~2X reduction of integration time to reach SNR**





Coronagraph SNR

- For the coronagraph the SNR is given by

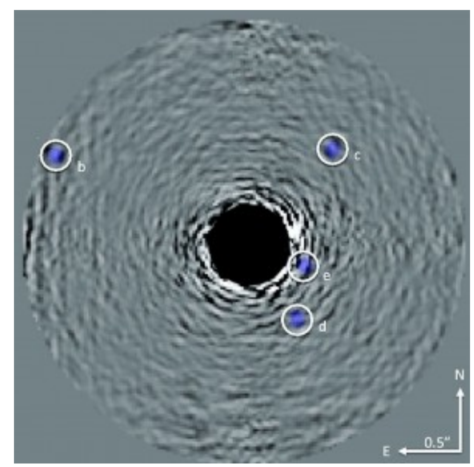
$$SNR = \frac{S}{N} \qquad \text{where:} \quad S = r_{pl}\, t \qquad r_{pl} = \Phi A \tau \eta \qquad \begin{cases} \Phi & : \text{photon flux} \\ A & : \text{collector area} \\ \tau & : \text{transmission} \\ \eta & : \text{QE} \end{cases}$$

$$N = \sqrt{\sigma_{shot}^2 + \sigma_{zodi}^2 + \sigma_{spec}^2 + \sigma_{spstr}^2 + \sigma_{\det}^2}$$

σ_{shot}^2	σ_{zodi}^2	σ_{spec}^2	σ_{spstr}^2	$\sigma_{\det}^2$
shot noise of planet light	shot noise from zodiacal dust (local + exo)	shot noise of mean speckle	residual speckle structure (after post-processing)	detector noise

Detector parameters of most importance:

1. QE
2. Read Noise
3. Dark current
4. Frame Rate
5. Clock-induced Charge (CIC)



Requisit Time to reach Goal SNR

- Accounting for the EM gain, the ENF and the CIC, the expression for the SNR can be written as:

$$SNR = \frac{S}{N} \quad \text{where} \quad \begin{cases} S = r_{pl}\, t & \text{where:} \quad r_{pl} = f_{SR} \cdot C_{pl} \Phi_{star} \cdot A \cdot \tau \cdot \eta \\ N = \sqrt{r_{noise}\, t + \sigma_{spstr}^2} & \end{cases}$$

$$r_{noise} = \underbrace{ENF^2 \cdot f_{SR} \cdot \left[C_{pl} \Phi_{star} + C_{CG} \Phi_{star} + \left(\left.\frac{d\Phi}{d\Omega}\right|_{zod} \Delta\Omega_{PSF} \right) \right] \cdot A \cdot \tau \cdot \eta}_{\text{photonic}} + \underbrace{ENF^2 \cdot \left[i_{dark} m_{pix} + q_{CIC} \frac{m_{pix}}{t_{frame}} \right] + \frac{m_{pix}}{t_{frame}} \cdot \left(\frac{\sigma_{read}}{G_{EM}} \right)^2}_{\text{electronic}}$$

$$\sigma_{spstr}^2 = n_{spec}\, t^2 \quad \text{where} \quad n_{spec} = \left(f_{pp} \cdot f_{SR} \cdot C_{CG} \Phi_{star} \cdot A \cdot \tau \cdot \eta \right)^2$$

Can invert the equation to get the requisite time to get to a desired SNR:

$$\rightarrow \quad \boxed{t = \frac{SNR^2 \cdot r_{noise}}{r_{pl}^2 - SNR^2 \cdot n_{spec}}}$$

Note that there could be <u>no solution</u> to *t* for sufficiently poor contrast!

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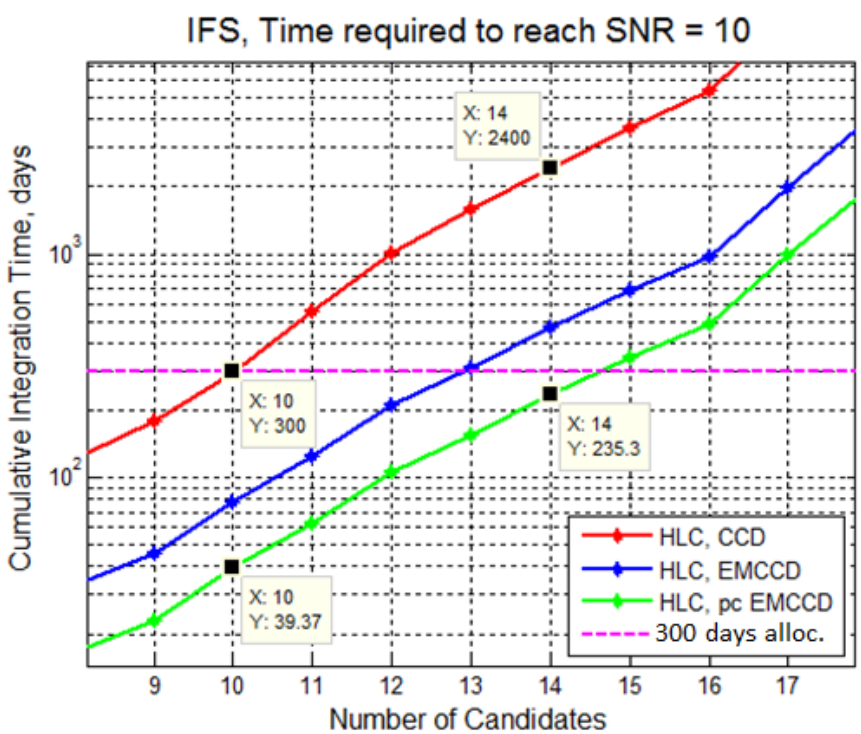
Comparison of Performance with Different Sensors

- Preliminary results of the detector SNR model and planet yield appear below
- This results indicate that, while we can have a workable mission with a conventional CCD, the use of an EMCCD will create 90% savings in integration time, lowering risk of target (null) acquisition and allowing time for more science
- This model is to be improved, including realistic integration times based on radiation environment analysis.



Assume:

- dark = 3e-4 e/pix/s,
- CIC = 1e-3 e/pix/fr,
- jitter = 0.4 mas,
- HLC coronagraph

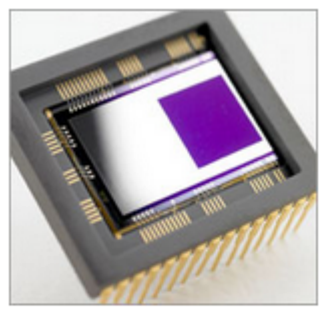
Option	CCD	EMCCD	PC EMCCD
Read Noise (e-)	3	8	8
EM Gain	1	40	200
ENF	1	1.41	1
Frame Rate (fps)	0.0005	0.0005	0.002

Focal Plane	Area (pix)	Width	Height	shape	SNR Target	SNR pixels	Light fract.
IFS	28	14	2	streak	9	4.0	0.143
Imaging	4.91	2.5	2.5	circle	5	4.91	1.0

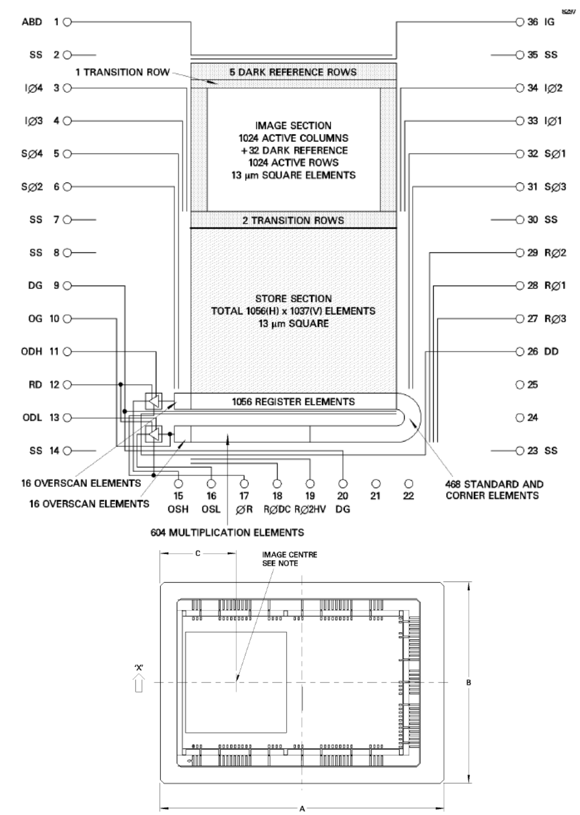
Detector Development Near Term

- We are working with industry partners (Canada, UK, France) in risk reduction activities
- The test lab is being moved from Caltech to JPL and testing activity is being accelerated
- We are now putting together a development plan consistent with the rough lead time estimates we are getting from the vendors

Test setup Control Electronics
(with flight possibility)
(NuVu Cameras, Canada)



CCD201 - EMCCD
(a candidate 1k x 1k CCD)
(e2v, UK)



Next Steps

- Technology Maturation:
  - Shaped pupil testbed Test Readiness Review (TRR) 4/3/2014
  - Detector vendor visit 5/18/2014
  - LOWFS concept review 5/15/2014
  - Hybrid Lyot mask delivery ~5/31/2014
- AFTA-WFIRST DRM:
  - Cycle 5 delivery 9/2014
  - SDT final report 1/2015
  - CATE 2/2015
- Wider community participation
  - International partnership

Acknowledgement

- Contributions from team members from JPL, GSFC, Princeton, Univ of Arizona, Ames, LLNL, STScI, Caltech

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